Introduction

With the ongoing concern about biodiversity loss, monitoring biodiversity at various levels of biological organisation is important [@pereira2013essential]. At the organismal level, biodiversity is generally measured by three components: number of species, total number of individuals (abundance), and how the individuals are distributed across species (evenness). We lose biodiversity if abundance decreases, if species go extinct, if communities become dominated by a few common species, or a combination of these processes. To measure changes in biodiversity, we need indicators that are sensitive to changes in these components [@bucklandMonitoringChangeBiodiversity2005; @buckland2017measuring].

One type of index that is sensitive to these three aspects of biodiversity change is based on aggregated species trends [@buckland2011geometric]. Let n_i be the number of individuals of species i and $n = \sum_{i=1}^{S} n_i$ the total number of individuals of S species in the community, so that $i = 1, \ldots, S$. Evenness measures how uniform the species proportions p_i are, where $p_i = n_i/n$. Now consider surveying a single location and counting the individuals of a group of species over time. The counts $n_{i,j}$ are the number of individuals encountered of species i in year j. Because population growth is a multiplicative process, changes in n_i over time are best measured as ratios $n_{i,j+1}/n_{i,j}$. Trends in the abundance of individual species can then be aggregated using the geometric mean [@buckland2011geometric] or equivalently, the arithmetic mean of the changes in log abundances $G_j = exp\left(\frac{1}{S}\sum_{i=1}^{S} log\frac{n_{i,j+1}}{n_{i,j}}\right)$. The well-known Living Planet Index, for example, is based on the geometric mean [@lohLivingPlanetIndex2005; @mcraeDiversityWeightedLivingPlanet2017] even though it measures change against a baseline, rather than from one year to the next.

The geometric mean weights all species trends equally and is therefore sensitive to samll clusters of species with extreme trends [@leungClusteredCatastrophicGlobal2020]. It is also sensitive to trends in rare species, which are often difficult to estimate well [@buckland2017measuring]. An alternative approach for measuring change in biodiversity is to calculate a biodiversity index for each year and then examine changes in this index over time. Many measures of diversity exist but the ones that can be interpreted as the effective number of species seem the most intuitive ones [@jost2006entropy]. One family of such diversity measures is the Hill numbers [@hillDiversityEvennessUnifying1973]:

$$^{q}D = \left(\sum_{i=1}^{S} p_i^q\right)^{1/(1-q)}$$

By varying the free parameter q, the Hill numbers are species richness for $q = 0$, the exponentiated Shannon entropy for $q = 1$ and the inverse of Simpson's index for $q = 2$.

When estimating trends in biodiversity, it is important to take into account the observation process that has given rise to the data. In most situations, it is impossible to census wild populations completely. We would like to know the number of individuals of species i, i.e. $n_{i,t}$, that is present in a population in year t. Instead, we obtain a count $c_{i,t}$ that is related to $n_{i,t}$ as $c_{i,t} = n_{i,t} \times p_{i,t}$ where $p_{i,t}$ is a detection rate. The observation process has three effects on the observed counts. 1) since $p_{i,t}$ usually varies because of variable conditions like weather, visibility, observer skills, characteristics of a species, etc., the counts are more variable than the actual population sizes [@link1994importance]. 2) The $p_{i,t}$ vary because some individuals escape detection and others might be double counted. Often, non-detection is a bigger issue than double counting and so the $p_{i,t}$ tend to be < 1. As a result, the raw counts tend to underestimate the true population sizes. 3) Sometimes, surveys are missed altogether, leading to $p_{i,t} = 0$ for all species in a particular year t.

Here, we explore trends in waterbird populations at a particular wetland, Barberspan, in South Africa. Waterbirds are an important component of biodiversity in wetlands and also often serve as indicators for the condition of their environment [@amatWaterbirdsBioindicatorsEnvironmental2010; @gregoryWildBirdIndicators2010; @sekerciogluIncreasingAwarenessAvian2006], such as the level of eutrophication of wetlands [@amatWaterbirdsBioindicatorsEnvironmental2010]. Waterbids are also notoriously difficult to count as they tend to flock and can uncooperatively fly around during surveys. The waterbirds at Barberspan have been counted twice per year, in mid winter and mid-summer, since 1993. However, as is often the case in long-term monitoring programmes, counts were not always carried out an the time series therefore contain gaps. We therefore estimate population sizes and their trends using state-space models to reduce the effect of the observation process [@auger-metheGuideStatespaceModeling2021]. We then calculate indices for biodiversity change by aggregating population trends and using biodiversity indicators.